EARTH OBSERVING SYSTEM (EOS) AQUA
LAUNCH AND EARLY MISSION ATTITUDE SUPPORT EXPERIENCES*

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ABSTRACT

The Earth Observing System (EOS) Aqua satellite was successfully launched on May 4, 2002. Aqua is the second in the series of EOS satellites. EOS is part of NASA's Earth Science Enterprise Program, whose goals are to advance the scientific understanding of the Earth system.

Aqua is a three-axis stabilized, Earth-pointing spacecraft in a nearly circular, sun-synchronous orbit at an altitude of 705 km.

The Goddard Space Flight Center (GSFC) Flight Dynamics attitude team supported all phases of the launch and early mission. This paper presents the main results and lessons learned during this period, including: real-time attitude mode transition support, sensor calibration, onboard computer attitude validation, response to spacecraft emergencies, postlaunch attitude analyses, and anomaly resolution.

In particular, Flight Dynamics support proved to be invaluable for successful Earth acquisition, fine-point mode transition, and recognition and correction of several anomalies, including support for the resolution of problems observed with the MODIS instrument.

INTRODUCTION

Aqua was successfully launched on May 4, 2002 at 09:54:58 UTC. It is the second in a series of four satellites that make up the Earth Observing System (EOS) program. The first EOS satellite to be launched was Terra (launched December 18, 1999); the third was ICESat (launched January 12, 2003); the last will be Aura (scheduled to launch in January of 2004). EOS is part of NASA's Earth Science Enterprise (ESE) and its scientific goals are to advance the understanding of the components of the Earth system, their interactions, and their changes over time.

Aqua is a three-axis stabilized, Earth pointing satellite. Nominally, its +z-axis is nadir pointing, its +y-axis is aligned with negative orbit normal, and its +x-axis points along (or near) the velocity vector. During science data collection Aqua is in Fine Point Mode (FPM), where: (1) it is targeted to an orbital coordinate system constructed from a Flight Dynamics generated onboard ephemeris, (2) it obtains its attitude knowledge from an onboard Kalman filter using measurements from two charge-coupled-device (CCD) star trackers and an inertial reference unit (IRU) package, and (3) it controls the attitude using four reaction wheels in conjunction with a magnetic torquer assembly. Aqua is in a sun-synchronous (approximately 1:30 pm local mean solar time at the ascending node), nearly circular orbit at an altitude of approximately 705 kilometers and an inclination of 98.2 degrees.

This paper highlights the major support activities and analyses carried out by the Flight Dynamics (FD) attitude team during launch and the early phases of the mission. Much of the support activity consisted of the execution of pre-planned procedures to meet known mission requirements, such as attitude mode transition support, attitude sensor calibration, and onboard computer (OBC) attitude validation. However, these activities led to the discovery of a number of anomalies, and provided key elements in their resolution.

ATTITUDE MODE TRANSITIONS

Following the separation of the satellite from the launch vehicle, Aqua undergoes a series of attitude control mode transitions before achieving its final science-collection attitude (FPM). Approximately 22 minutes after separation, the spacecraft is commanded to Sun Point Mode (SPM), at which time Aqua slews to an attitude where its –x-axis is pointed towards the Sun. The solar array is held fixed in its indexed position, such that its active side is constantly pointed towards the Sun. Soon after sun pointing is achieved, Aqua's roll rate is commanded to a magnitude of 1.8 times the rate of 1 revolution per orbit (RPO), spinning in a positive sense about the –x-axis (corresponding to a roll rate of approximately -0.108 degrees/second). It remains in this power/thermal safe mode for approximately 24 hours, at which time the FD attitude team and the Flight Operations Team (FOT) begin the procedures to place Aqua into Earth Point Mode (EPM), the details of which are explained below. Once in EPM, again these two teams can begin the procedures to place Aqua into FPM, which is the final target attitude mode for scientific observations to begin. The details of this transition are also explained below.

Sun Point Mode to Earth Point Mode Transition

The general strategy for achieving EPM is to command the transition from SPM to EPM at a time when the spacecraft is as close to an earth-pointing attitude as possible. In terms of the pitch angle, this is achieved by always performing the transition at 18:00 Local Satellite Time (LST). Since the –x-axis is nominally pointed to the Sun in SPM, it is at 6 hours after spacecraft noon (or 18:00 LST) that the rotating Y-Z plane most closely aligns with the nadir vector (the vector from the spacecraft to the center of the earth). This, in turn, brings the pitch angle (as referenced to a typical orbital coordinate system) as close to zero as possible. Optimizing the roll angle is somewhat trickier. The strategy is to adjust the –1.8 RPO roll rate so that the +z-axis will be as close to nadir-pointing as possible when the satellite reaches 18:00 LST. By optimizing the roll and pitch angles in this way, the probability of the Earth sensor locking onto the Earth at the time of the commanded transition is increased, and a successful SPM to EPM transition is more likely to be achieved.

To support the first level of strategy, the FD attitude team developed a utility to convert LST times to calendar times. A product containing the next ~24 hours of 18:00 LST times is delivered to the FOT, and based on these times, a target SPM to EPM transition is selected. To support the calculation of the adjusted roll rate, the FD attitude team developed a versatile utility named Rollman (for Roll Maneuver) that would compute the necessary roll rate to optimize the roll phase at the time of the transition. The procedures for generating this commanded roll rate adjustment begin approximately 4 hours before the target transition time. First, FD analysts must get a fairly accurate estimate of the current spacecraft attitude, which is a critical input into the Rollman utility. The attitude is obtained using the FD-developed Real-Time Attitude Determination System (RTADS), which ingests real-time telemetry to compute an attitude solution. Using only Coarse Sun sensor (CSS) data and Three-Axis Magnetometer (TAM) data, and orbit information from an FD-generated ground ephemeris, RTADS generates a real-time attitude quaternion solution, which is fed into Rollman. Rollman computes the desired roll rate and generates a product containing, among other things, the new roll rate and the time that the new roll rate must be invoked onboard. The FOT takes this product and builds a stored command sequence, which is uplinked to the spacecraft. Nominally, the new rate is invoked onboard at 21:00 LST, some 86 minutes prior to the transition to EPM. At the time of the transition, a variety of spacecraft flags are used to monitor the transition and to assess its success, including various Earth sensor flags, and the actual mode change flag itself.

The procedures and software utilities outlined above have been extremely successful in both pre-launch simulations and during the mission, having always resulted in a successful transition to date. On orbit, the procedures have been executed twice for Aqua. The first was the nominal transition, which occurred on the second day of the mission (May 5, 2002). The second time was during recovery from the first spacecraft emergency, in which Aqua autonomously transitioned back to SPM; this led to an SPM to EPM transition on May 20, 2002.

Earth Point Mode to Fine Point Mode Transition

Before transitioning to FPM, Aqua must successfully begin identifying stars using the onboard star identification algorithm. In order to achieve this, the algorithm must be given a fairly accurate initial attitude, meeting the accuracy requirements of 5 degrees in pitch and roll and 6 degrees in yaw. It is up to the FD attitude team to supply the spacecraft with this initial attitude. The general strategy is for RTADS to supply this attitude quaternion using star tracker data telemetered to the ground in real-time, and to subsequently uplink this initial attitude to the spacecraft.

During EPM, the roll and pitch angles are controlled by the Earth sensor to within 2–3 degrees of nominal; thus, the 5 degree requirement would be easily met. Although yaw is initially controlled in EPM using a combination of CSS and TAM measurements, the plan was that this control would shift to gyro control at some point before onboard star identification was to be attempted. It was thought that switching to gyro control would stabilize the yaw angle at whatever angle it happened to be at the time of the switch, and that this constant yaw angle could be determined by RTADS well within the 6 degree accuracy requirement. Moreover, since the yaw angle was predicted to be constant, the time between its determination and its uplink to the spacecraft would not be a factor. During pre-launch simulations of this activity, it was found that the yaw angle was not constant, and its behavior was not of a sufficient predictability to confidently meet the 6-degree accuracy requirement. It was clear that a new strategy had to be implemented.

The solution arrived at by the FD attitude team was to enhance the capability of RTADS to (1) capture a good star-tracker-based attitude solution at the press of a GUI-driven button on the RTADS display, (2) propagate this attitude any number of minutes into the future using user-selected rates on each of the three axes, and (3) deliver this quaternion solution quickly to the FOT for immediate uplink to the spacecraft, again at the press of a GUI-driven button on the RTADS display. This software and procedural enhancement solved the problem of a changing yaw angle by (1) accounting for a changing yaw by applying an estimated yaw rate over a short period of time, and (2) invoking this propagated attitude onboard before a significant propagation error could be accumulated. Pre-launch simulations proved this to be a viable method and successful onboard star identifications were achieved. After some practice at this time-critical activity, the total time required to capture, propagate, deliver, and uplink the RTADS-generated quaternion was reduced to 3 minutes. By reducing the propagation period to such a short duration, the propagation errors induced by applying predicted (and potentially incorrect) attitude rates are kept to a minimum.

On orbit, this procedure was executed on six occasions. The first two mark the first attempts to go from EPM to FPM (see the discussion under "Star Tracker Alignment Calibration" for an explanation of why this had to be done twice). The next four were in response to spacecraft emergencies, in which the spacecraft autonomously transitioned out of FPM into either EPM or SPM, and recovery activities included transition back to FPM. Table 1 summarizes the attitude accuracy results for all of these cases, indicating the errors induced by (1) the star-tracker-based attitude determined by RTADS, (2) the propagation of this attitude to the targeted command time, and (3) not applying the propagated attitude at precisely the targeted command time. Note that in an effort to be conservative, the FD attitude team and FOT analysts gave themselves 5 minutes to complete the procedure the first time it was attempted on-orbit. For subsequent events, as confidence in the procedure increased, the allotted time was reduced to 4 and then to 3 minutes. In all cases, the "5-5-6" degree accuracy requirement was met.

SENSOR CALIBRATION

Soon after launch several of the Aqua attitude sensors were calibrated. The alignment of the star trackers was refined in order to improve attitude accuracy in FPM, the alignments and scale factors of the gyros were determined in order to improve maneuver accuracy, and the alignments, scale factors, and biases of the magnetometers were determined to improve attitude accuracy in SPM and EPM.

For Aqua, the star tracker alignment and magnetometer calibrations were particularly important in that they provided indications of inconsistent values of the nominal star tracker alignments and the magnetic field model. These calibration results indicated the need for further analysis, which led to several onboard corrections.

Star Tracker Alignment Calibration

The first attempt to determine the on-orbit star tracker alignments was performed in the short period after the star trackers were activated, but before the first attempted transition from EPM to FPM (see Reference 1 for a description of the algorithms used for alignment calibration). This initial alignment determination showed a difference of more than 0.2 deg from prelaunch values. It corresponds to a 1:2:3 sensor frame rotation of 0.23, 0.05, and 0.04 deg. The major cause of this extremely large misalignment was later traced to an error in the onboard nominal alignments.

The large effective misalignments caused the onboard star identification process to fail (first attempted on May 8, 2002). The logic for this process requires an approximate attitude (within a few degrees) to be used in a direct match star identification algorithm to identify stars in tracker 1. The identity of these stars is used to determine a more accurate attitude, based on tracker 1 measurements only. The more accurate attitude is then used, along with

the relative alignments of the two trackers, to predict small search windows (75 arcsec on a side) within which stars are expected to be found in tracker 2. Because of the 0.2 deg alignment errors, the predicted star positions in tracker 2 were consistently outside the search windows, and were neither tracked nor identified. On the following day (May 9, 2002), post-calibration alignment matrices were uplinked to the spacecraft, and the onboard star identification process was attempted again. This second attempt proceeded without difficulty.

Table 1. Summary of Actual Uplink Quaternion Accuracy and Sources of Error

		Initial Attempt #1	Initial Attempt #2	Spacecraft Emergency #1	Spacecraft Emergency #2	Spacecraft Emergency #3	Spacecraft Emergency #4
DOY 2002		128	129	141	179	211	255
Propagation rates (deg/sec)	R	0.000	0.000	0.000	0.000	0.000	0.000
	P	0.000	0.000	0.000	0.000	0.000	0.000
	Y	0.000	0.014	0.002	0.000	0.020	0.000
RTADS error (deg)	R	-0.25	0.08	0.09	0.01	0.05	-0.02
	P	0.51	-2.41	0.60	0.00	-0.05	-0.02
	Y	-0.08	-0.33	-0.08	0.00	-0.01	-0.01
Propagation time (min)		5	4	4	4	4	3
Propagation error (deg)	R	0.50	1.11	0.09	0.43	2.12	0.23
	P	-0.47	0.08	-0.20	0.64	-2.38	0.15
	Y	-2.91	0.97	0.14	4.24	1.00	0.62
Error in time of uplink command (sec)		3	10	-46	2	7	3
Error due to timing of uplink (deg)	R	-0.04	0.02	0.57	0.00	0.05	0.00
	P	0.15	0.57	-2.80	0.11	0.42	0.15
	Y	0.01	0.01	0.09	-0.01	0.01	0.00
Total error at time of command (deg)	R	0.28	1.23	0.75	0.32	2.21	0.20
	P	0.15	-1.90	-2.40	0.87	-2.10	0.28
	Y	-3.03	0.58	0.15	4.28	0.92	0.62

When the proper nominal alignments were verified and used, a definitive calibration was performed. This resulted in tracker 2 misalignments corresponding to a 1:2:3 sensor frame rotation of 0.003, 0.007, and -0.004 deg—much more in keeping with expectations.

The pre- and post-calibration star tracker residuals are shown in Fig. 1.

Inertial Reference Unit Calibration

Measured attitude rates are corrected to compensate for alignments, scale factors, and biases by the function:

$$\vec{\omega}_{adj} = G\vec{\omega}_{obs} - \vec{b} \tag{1}$$

where $\vec{\omega}_{adj}$ and $\vec{\omega}_{obs}$ are the adjusted and observed rate vectors, G is a combined alignment and scale factor matrix (transforms from true sensor to body), and $\vec{b}$ is a bias vector in the body frame.
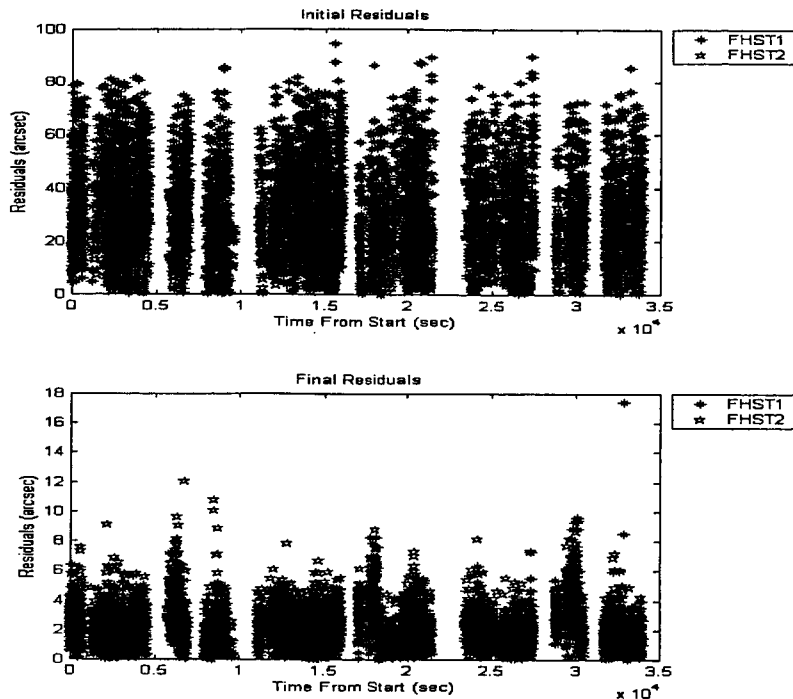
Figure 1. Pre- and Post-Definitive Star Tracker Alignment Calibration

To calibrate Aqua's gyros, a series of maneuvers was performed to produce sufficient data. The algorithms used for calibration are described in Reference 2. These maneuvers consisted of a 25 deg slew around one body axis, a pause at the offset attitude for several minutes, and a slew back to nominal (angles are measured relative to the Orbital Coordinate System). This sequence is then repeated in the opposite direction; thus, each axis experiences a total of 4 rotations. The entire series of rotations and constant attitude periods are repeated for each body axis. The gyro rates during all of these maneuvers are shown in Fig. 2.

Two features of these rates are noteworthy. There is a significant data gap at approximately 04:10Z and there are large X-axis vibrations due to the unbalanced rotation of the Advanced Microwave Scanning Radiometer—EOS (AMSR-E) instrument. The data gap reduced the usefulness (for calibration) of the maneuvers near it and the large vibrations decreased the calibration accuracy.

The calibration was performed using the Batch Least-Squares IRU Calibration utility (BICal) using 3 of the 4 rotations about each axis. The other rotation was reserved for validation of the results. Of the yaw maneuvers, the first, second, and fourth were used for BICal, while for pitch and roll, the first three were used.

The calibration results were validated in the following manner. Sensor data from the constant rate periods of the validation maneuvers were used to compute attitudes and effective gyro biases during these periods. Because these periods have nearly constant rates, the attitude accuracy is only weakly affected by gyro parameter errors. Thus these attitudes have accuracies limited only by the number and accuracy of the star tracker observations and will be referred to as "truth" attitudes. For each maneuver, a "truth" attitude was propagated through the maneuver using the pre-calibration or post-calibration G-matrix and biases. The resulting post-maneuver propagated attitudes were compared to the post-maneuver "truth" attitudes.

The results of these comparisons are given in Table 2 showing the significant improvement in the accuracy of the gyro-propagated attitude.

A useful measure of the significance of the calibration is obtained by comparing the BICal G-matrix and the identity matrix (no calibration) applied to 90 deg slews, for example. Neglecting any error arising from gyro biases which are solved for by the onboard Kalman filter, the rotation errors from 90 deg slews about the X-, Y-, and Z-axes are given in Table 3. These numbers are a measure of the total improvement provided by the IRU calibration.
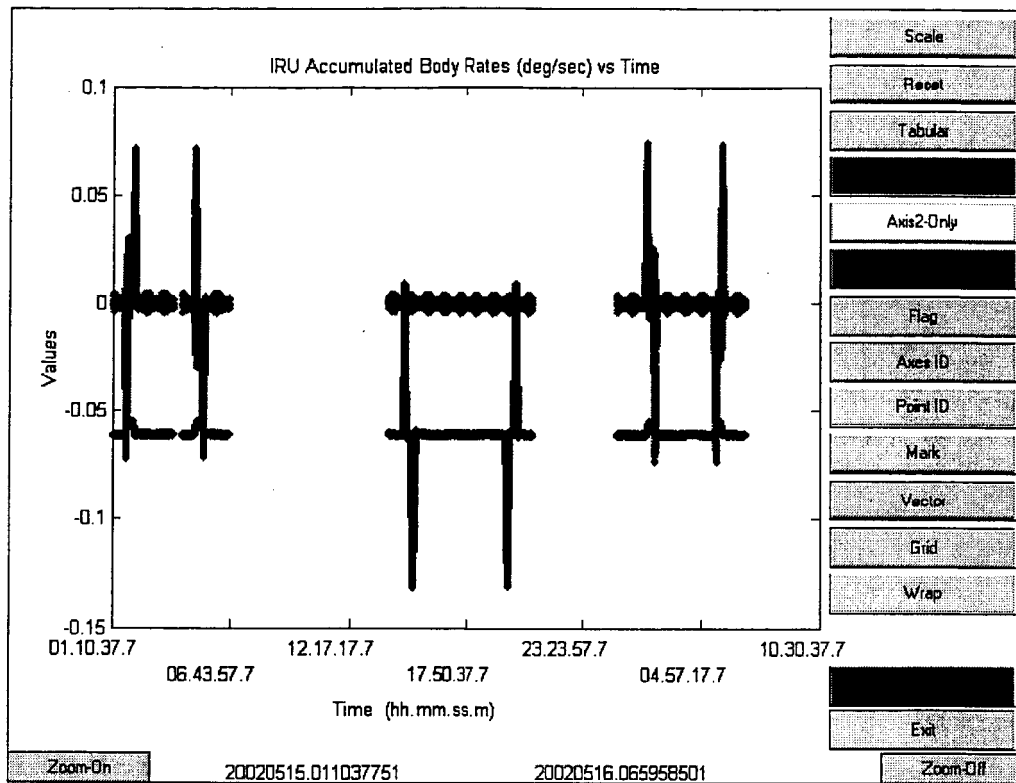
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Figure 2. Body rates during the gyro calibration maneuvers. The first grouping shows the 4 yaw rotations; the second grouping shows the 4 pitch rotations (note the nominal pitch rate of -0.06 deg/sec); the third grouping shows the 4 roll rotations.

Table 2. BICal Validation Results

Validation Maneuver	Axis	RMS differences between propagated and "truth" attitudes (deg)	
		pre-calibration	post-calibration
	X	0.020	0.006
Yaw	Y	0.012	0.005
	Z	0.003	0.002
	X	0.004	0.001
Pitch	Y	0.010	0.002
	Z	0.024	0.001
	X	0.005	0.003
Roll	Y	0.007	0.001
	Z	0.015	0.002

Table 3. Rotation Errors from 90 deg Slews about X-, Y-, and Z-axes.
(These errors are removed by the BICal calibration)

Slew/ Rotation Axis	Error about X-axis (arc sec)	Error about Y-axis (arc sec)	Error about Z-axis (arc sec)	Total Rotation Error (arc sec)
90 deg /X	67.4863	-41.5714	-159.8068	178.3838
90 deg / Y	118.5890	-133.4472	282.4670	334.1543
90 deg / Z	-59.1596	-190.4771	-18.9385	200.3498

Three Axis Magnetometer Calibration

Measured magnetic field vectors, $\vec{B}_{obs}$ are corrected to compensate for alignments, scale factors, and biases by the function:

$$\vec{B}_{adj} = AM(S\vec{B}_{obs} - \vec{b}) \qquad (2)$$

where $\vec{B}_{obs}$ and $\vec{B}_{adj}$ are the observed and adjusted magnetic field vectors, A is the nominal sensor alignment, M is a misalignment matrix, S is a diagonal scale factor matrix and $\vec{b}$ is a bias vector. Determination of these parameters was performed by minimizing the differences between adjusted measurements and those computed using an accurate magnetic field model. This minimization uses an attitude estimate to convert model vectors into the body frame.

Preliminary (coarse) TAM-1 calibration was performed in Earth Point Mode using about 4 hours of telemetry using ground-calculated, star-tracker-based attitudes. The coarse TAM-1 calibration computed biases only, and resulted in about 10 mG reductions in the residuals.

TAM-1 was fully calibrated using 10 hours (over 20000 TAM-1 measurements) of telemetry spanning 20020509.210000 to 20020510.060000 (YYYYMMDD.hhmmss) in FPM. Sufficiently accurate, star-tracker-based onboard attitude estimates were available and were used for calibration. Pre- and post-calibration magnetic field residuals for TAM-1 are shown in Fig. 3.
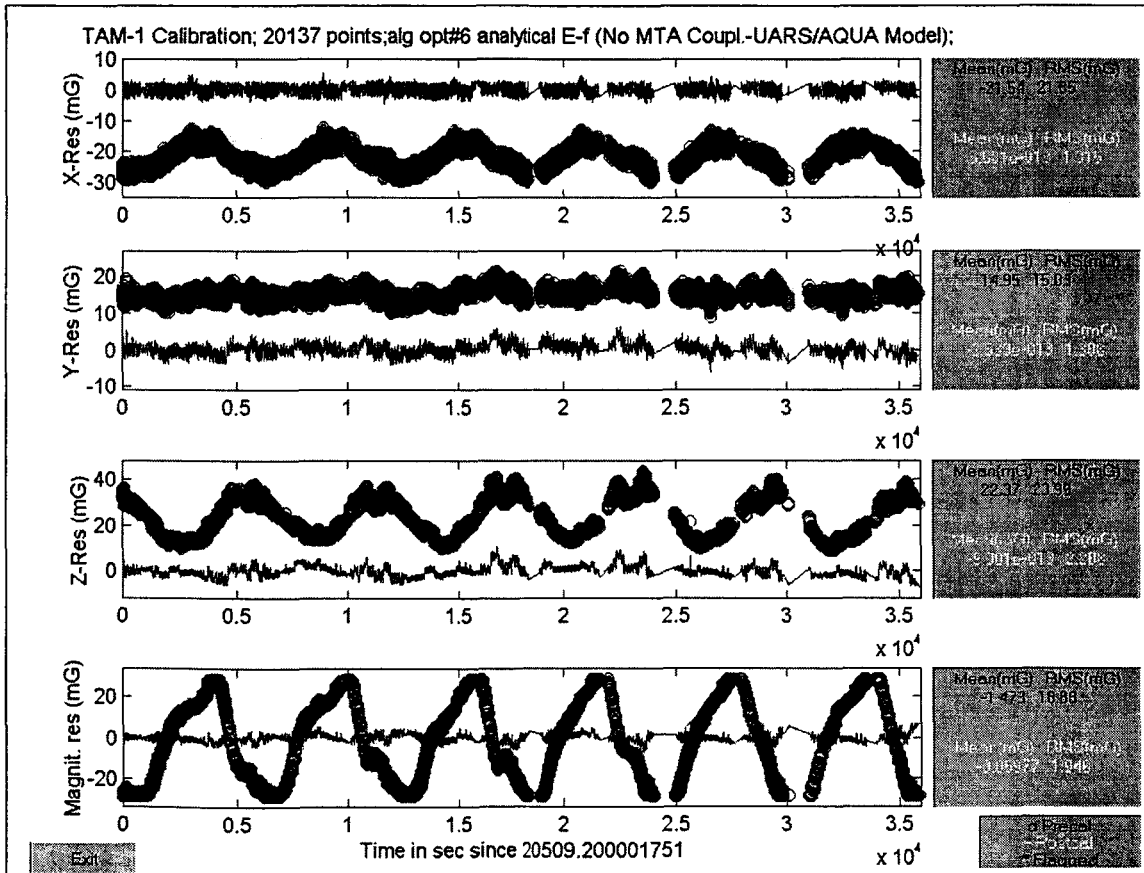

Figure 3. TAM-1 Residuals Using Pre- (circles) and Post-Calibration (solid lines) Parameters

The numerical values of the TAM-1 calibration parameters were quite different from prelaunch values and consistently yielded small residuals when applied to other data. After activation of the science instruments, the

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residuals increased by a factor of 2-3, but were still far lower than before calibration. It is probable that magnetic fields generated in the operation of the science instruments, contaminate the magnetometer observations.

TAM-2 was calibrated using the 10 hours of data (approximately 19000 TAM-2 measurements) spanning 20020514.231644 to 20020515.060000. Similarly to TAM-1, TAM-2 parameters, especially the biases, showed significant changes from prelaunch values. The residuals before and after TAM-2 calibration are shown in Fig. 4.
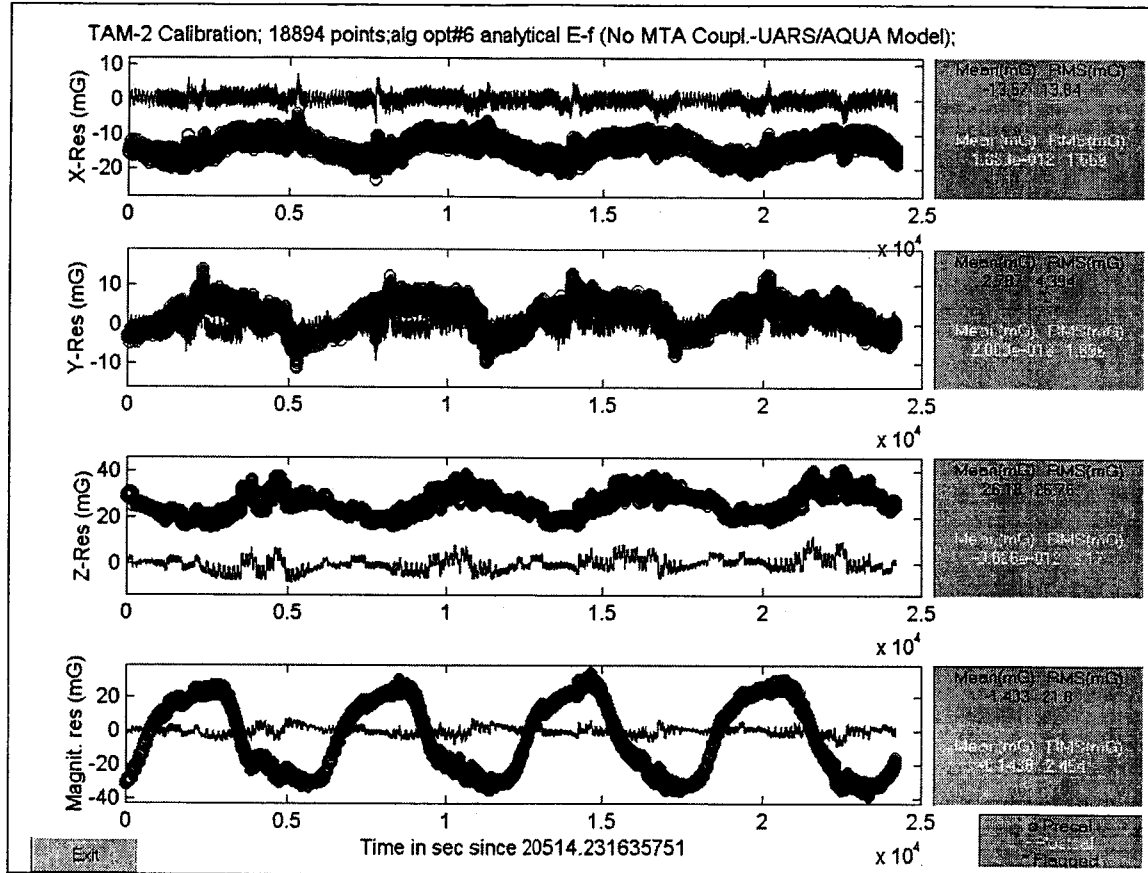

Figure 4. TAM-2 Residuals Using Pre- (circles) and Post-Calibration (solid lines) Parameters

OBC VALIDATION

Validation of the onboard attitude estimates was made difficult by several factors. Initially, the onboard system had an inconsistency between the star catalog and ephemeris coordinate systems (see the discussion of the MODIS attitude anomaly below). This resulted in large (up to ±150 arcsec) differences between ground and onboard attitude estimates.

After correcting for the coordinate system error, a smaller effect became observable. OBC validation revealed systematic offsets in the pitch and roll attitudes of 13 and 11 arcsec, respectively. An analysis was undertaken to find the source of the offsets. It was found that a 125 msec timetag error in star tracker 1 would exactly account for the observed offsets. The error was later traced to a star tracker timetag error in the onboard processing.

After corrections were applied for these factors, the OBC attitudes differed from ground calculations by less than 1 arcsec in their mean values, but oscillations in the differences resulted in standard deviations of 8.1, 5.5, and 8.0 arcsec for roll, pitch and yaw respectively. These represent the best current estimates of onboard attitude accuracy.

The exact source of these oscillations is still under investigation but several correlations have been made. The relative alignment of the two star trackers was correlated with the star tracker baseplate temperature with a misalignment amplitude of as much as 5 arcsec. Similarly (and perhaps due to star tracker misalignment variation)

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the OBC gyro bias estimates varied regularly with the same period as the temperature variation. There was, however, no simple correlation between these biases and temperature. It is possible that a correlation between temperature gradients, or some function of temperature history exists.

Star tracker baseplate temperatures show an orbital oscillation. Superimposed on this oscillation is a general cooling trend. When the temperature falls below a limit, a heater is activated and the temperature rises. Early in the mission the heater was activated every four orbits, but by June 2003 it was activated every 3 orbits. Therefore, in the June period, the temperature has a pattern that repeated every 3 orbits. The range of temperatures was about 3 deg, and the repetition was within 0.1 deg. Both misalignments and gyro biases show a 3-orbit cycle and when the heater is activated, and the temperature changes rapidly, both change noticeably.

Although the cause of the apparent correlation among temperature, misalignment, gyro bias, and attitude error are being investigated, the current attitude accuracy estimates are well within requirements.

ANOMALY RESOLUTION

In this section, we discuss some of the observed anomalies encountered during the early phases of the Aqua mission, and the analyses carried out by the Flight Dynamics attitude team in an effort to identify the source of these anomalies. The results of these anomaly studies are also presented.

Onboard Magnetic Field Model

Early in the mission it was found that Aqua was experiencing large excursions in yaw angle while in Earth Point Mode. It was known that knowledge of the yaw angle would be limited by the coarseness of the sensors used in this mode (CSS, Earth Sensor Assembly [ESA], and TAM), but the errors were significantly larger than expected (at times approaching 50 deg). We eventually traced this to an error in the onboard magnetic field reference model. We found large differences between the onboard and ground magnetic field models; the angular difference between the onboard and ground vectors had a maximum value of 11.1 deg and a standard deviation of 2.7 deg.

Both the onboard and ground magnetic field reference models use the published International Geomagnetic Reference Field (IGRF) model (Ref. 3). However, the onboard flight software does not apply the secular correction to the coefficients. Instead, it always uses coefficients that are already propagated forward to January 1, 2004, roughly mid-mission. We verified that these epoch-2004 coefficients agree with the ground software model coefficients propagated to that time. We also verified the onboard coefficients are correctly normalized. The ground software applies a Schmidt normalization each time the field is computed, whereas the onboard system includes the normalization factors in the uplinked coefficients. The flight software specifications of the IGRF model are consistent with this choice.

To validate the onboard reference field model, we implemented the field model flight software specifications using MATLAB® (The MathWorks, Inc.). It was immediately found that the model as specified did not agree with the Flight Dynamics ground support software. Next, it was verified that this test implementation of the flight software agreed well with reference field values in telemetry; that is, it correctly represented the actual onboard software.

Examination of the flight software specifications and comparison with a theoretical description of the IGRF model led to the discovery of a small error in the specifications, which had been implemented in the flight software. When this error was corrected in the MATLAB implementation of the flight software, the discrepancy with the ground support software disappeared. The maximum error was reduced to 0.00076 deg.

The other known errors in the onboard field model are small compared to the coarse sensor accuracies. The model is limited to 5th-order while the IGRF is a 10th-order model; this causes errors in the field direction with standard deviation of 0.28 deg, although there are spikes up to 1.5 deg. The use of epoch-2004 coefficients with no secular correction produced errors at the time of launch of less than 0.5 deg with standard deviation of 0.08 deg.

When the correction to the onboard software was uplinked, the error in the EPM onboard yaw estimate decreased from 18 deg to 5.9 deg (1σ). A part of this improvement was due to improved TAM calibration parameters which were uploaded at the same time, but this was expected to have a smaller effect.

The actual EPM yaw control could take better advantage of the improved onboard yaw estimate by changing the tolerance on the ESA/TAM coalignment angle. This tolerance was initially set to discard the ESA/TAM solutions if the coalignment is closer than 35 deg. With the improved magnetic field model, much closer coalignments are

acceptable. If the spacecraft is allowed to use more of these ESA/TAM attitude solutions for EPM control, it would be able to avoid using the less accurate CSS or simply drifting, as is currently the case when no Sun data is available. The coalignment tolerance was eventually decreased from 35 to 10 deg.

Thruster Plume Impingement

In preparation for the Aqua ascent burns, an engineering test thruster burn was performed on May 11, 2002. After this burn, the attitude was controlled and brought back to nominal using thrusters in Attitude Hold Mode (AHM). The attitude response was found to be anomalous. Possible causes included thruster misalignment, error in the spacecraft center of mass (C.M.) estimate, or thruster plume impingement. It was unlikely that errors in thruster mounting or C.M. location could be large enough to explain the anomaly; however, if the exhaust cones of thrusters 1 and 2 were large enough, they could be impinging on the X-band antenna mast. It was decided to compare predicted and measured angular rate changes from a series of small burns to try to estimate thruster and C.M. parameters.

A series of 1-sec burns for each thruster was performed on May 31, 2002. This provided data for all 4 thrusters, but vibrations of the solar arrays and the rapid control system response via the reaction wheels made the analysis difficult. Rough corrections for these error sources were obtained by fitting the rate data and estimating the rate that a rigid body would have had at the end of each burn. We found it was not possible to separate C.M. location from thruster parameters, but we could solve for an effective thrust vector: two components were observable from the rate data and the third was obtained by minimizing the angle between the estimated and nominal thrust vectors. Details are given in Ref. 4.

Even with the corrections for vibrations and control system response and averaging over 3 separate burns for each thruster, there were still significant uncertainties in the estimated angular momentum changes. Nonetheless, thrusters 1 and 2 showed the largest apparent angular deviations from their nominal mounting angles with shifts of 4.0 and 5.6 deg, respectively. This offered corroboration for the partial plume impingement on the X-band antenna mast suggested for these two thrusters. The direction of the angular shift of the thrust vectors was also consistent with plume impingement. Because of their placement, no plume impingement was likely for thrusters 3 and 4, and it was found that their apparent deviations from nominal were less than 1/3 as large as those of thrusters 1 and 2.

MODIS Attitude Anomaly

The Aqua Flight Dynamics attitude analysts became involved in efforts to resolve an attitude anomaly observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument. In October 2002, MODIS personnel presented a large amount of geolocation data showing that the MODIS instrument was detecting significant yaw errors. These errors were not constant and could not be removed with a simple bias. The apparent range of yaw angles initially reported was 100 arcsec. During this same period, the Flight Dynamics team was also investigating the discrepancy between the onboard and ground attitude estimates pertinent to validating the onboard attitude. This discrepancy was much smaller than the MODIS yaw errors, but there was suspicion of a connection and much of the analysis effort proceeded in parallel.

Aqua, MODIS, Flight Dynamics, and other GSFC support personnel met several times from October 2002 to February 2003 to discuss Aqua attitude accuracy. The MODIS instrument was indicating a peak-to-peak yaw error of 100 arcsec compared to the onboard computer (OBC) estimate. Our attitude estimates and comparisons with the OBC indicated errors usually under 25 arcsec. At the first MODIS anomaly resolution meeting, we suggested the MODIS attitude errors could be dependent on latitude. This was based on a correlation between the number of positive and negative residuals with the number of control points in the northern and southern hemispheres. This dependence was quickly verified by MODIS personnel.

The MODIS ground software requires the attitude to be represented as Euler angles in the orbital coordinate system (OCS). Flight Dynamics provided solutions converted to OCS roll, pitch, and yaw for several tests by the MODIS analysts. The tests verified that neither the corrections for time-varying gyro bias nor the difference between predictive and definitive ephemerides could explain the anomalous MODIS values.

In January, 2003, a MODIS analyst suggested the inertial coordinate system as used on board be investigated. This reference frame is defined in terms of the Earth's polar axis and the direction of the vernal equinox. These defining vectors are time-dependent due to torques imparted by the Moon, Sun, and planets. There is a secular precession of the equinox amounting to about 50 arcsec per year and a periodic nutation of roughly 15 arcsec with predominant

period of 18.6 years (Ref. 5). These are shown in Figure 5. Three common ways to define the inertial frame are to use the true pole and equinox vectors on the date of interest (TOD), to use the mean vectors on the date of interest (MOD), or to use the mean vectors at the arbitrarily chosen standard epoch of Julian January 1, 2000 (J2000). True-of-date vectors account for both precession and nutation while mean-of-date vectors account only for precession relative to the J2000 epoch.
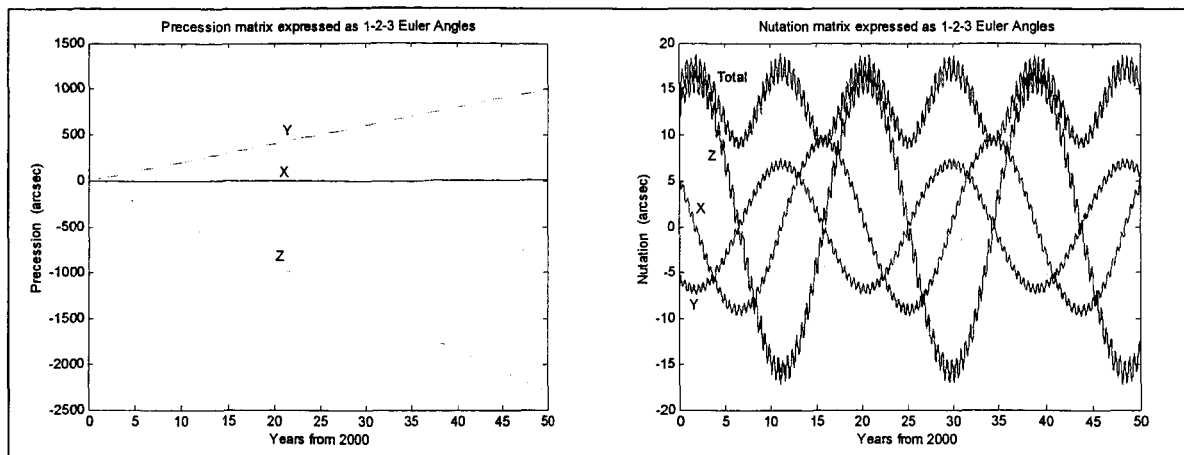

Figure 5. *(left)* **Precession correction expressed as rotations (arcsec) about the J2000 axes.** *(right)* **Nutation correction expressed as rotations (arcsec) about the MOD axes. The main periodicities are at 18.6 years, half year, and half month.**

It was found that the Aqua onboard control system was using a J2000 spacecraft ephemeris (which defines the target quaternion) and an MOD star catalog (i.e., a J2000 star catalog with corrections for precession, which is used when computing the onboard attitude). This inconsistency led to large spacecraft pointing errors in OCS (see below). One reason that FD analysts had not detected any large attitude excursions in ground-based solutions was that focus had been placed in OBC validation procedures (the requirement specified in the Mission Support Requirements Document [MSRD]), which used an ephemeris-independent quaternion comparison method. This comparison would not have detected the coordinate system mismatch between the onboard ephemeris and onboard star catalog. The comparison results yielded larger-than-expected discrepancies between the ground and onboard quaternions on the order of the full 25 arcsec knowledge budget. This discrepancy was later explained when it was discovered that the onboard star catalog positions were corrected to MOD, while ground star catalog positions were corrected to TOD (precession and nutation corrections applied). In addition, ground Euler angles were in error since the TOD ground quaternions were being converted to Euler angles with a J2000 ephemeris. To avoid coordinate system mismatches in ground-based processing in the future, the FDS attitude determination software will be enhanced to include a warning to the user when applying star catalog position corrections, and to ensure that the corrections are appropriate to the future application of the star-tracker-based attitude solution (e.g., conversion to Euler angles with an ephemeris, or comparison with an onboard quaternion).

To determine the impact of the onboard error, FD analysts computed attitudes using a J2000 star catalog and expressed them in OCS using a consistent J2000 ephemeris. The OCS ground-based attitudes showed a 70 arcsec pitch offset and 1/4-orbit coupled roll and yaw errors of 250 arcsec, peak-to-peak. This accurately represents the actual Aqua spacecraft attitude at that time; the magnitude of these errors had been growing by 50 arcsec per year (RSS) since 2000, in agreement with Figure 5.

To make the connection with the errors observed by MODIS, Figure 6 shows the differences between the attitudes computed with a J2000 and a MOD star catalog. These are plotted versus orbit phase measured from the ascending node. It was quickly determined that Figure 6 agrees very well with errors reported by the MODIS analysts. This agreement is seen in Figure 7 where the upper part (from Ref. 6, with permission) shows the observed MODIS attitude errors versus latitudinal zone number and the lower part is a detail from Figure 6 showing only the orbit phases corresponding to the MODIS zone numbers. The offsets are different between these two figures because biases had been applied to the MODIS data to remove as much of the error as possible, but the shape and peak-to-peak range of the errors agree very well.
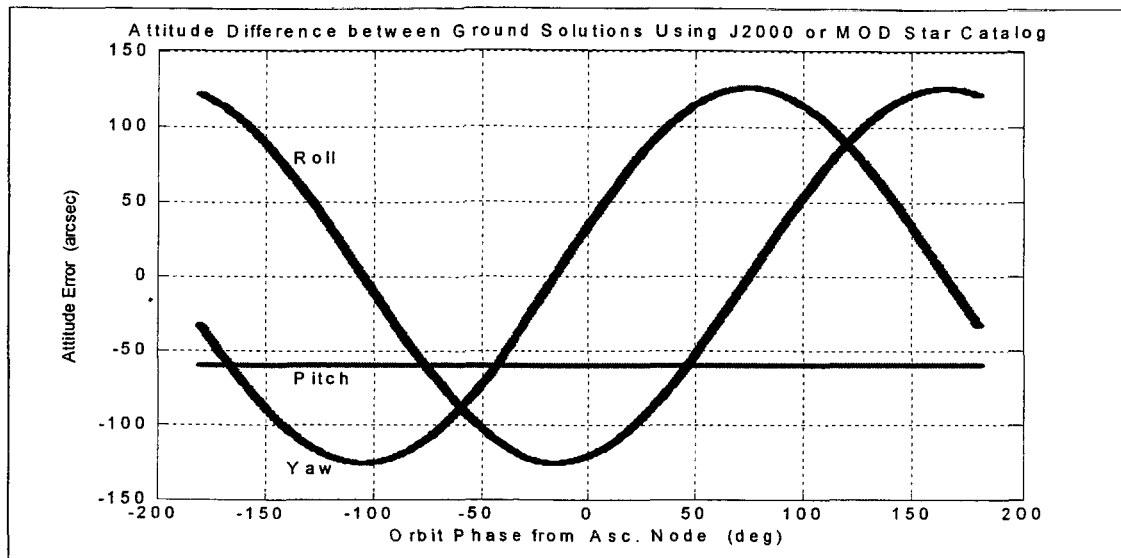
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Figure 6. Difference (arcsec) between ground attitude solutions for Oct. 8, 2002 using J2000 and MOD star catalogs plotted as a function of the orbit phase measured from the ascending node.

As a second test, attitudes computed using the J2000 star catalog and converted to OCS using a J2000 definitive ephemeris were delivered for processing by the MODIS software. For all cases, the MODIS team found the attitude errors were substantially reduced from those using MOD attitudes from the spacecraft OBC.

Thus, it was clear that the MODIS attitude problem was caused by two separate coordinate frame mismatches. First, the onboard attitude was determined using an MOD star catalog. This meant the onboard estimated quaternions represented rotations from the MOD geocentric inertial frame to the body frame. It was then converted incorrectly by the ground data processing utility (DPREP) to Euler angles using the J2000 ephemeris. These incorrect Euler angles were ingested by the MODIS software.

Secondly, the target attitude was computed on board using the uplinked J2000 ephemeris while the estimated attitude was computed by the OBC Kalman Filter using the MOD star catalog. This led to actual pointing errors over 250 arcsec peak-to-peak.

We should emphasize that the actual spacecraft control would be completely unaffected by the choice of coordinate system epoch as long as the onboard "target" and "knowledge" coordinate systems are consistent. Use of a TOD star catalog does not improve the spacecraft pointing accuracy (other time-dependent corrections for velocity aberration and proper motion are handled separately). The instantaneous angles between the star vectors, the spacecraft position and velocity, and the body axes are all independent of the frame in which these vectors are represented.

Resolution of the anomaly had three parts. First, the DPREP coordinate frame inconsistency had to be removed so future MODIS processing would receive correct Euler angles. Second, the onboard coordinate frame inconsistency had to be removed to eliminate the large pointing error in OCS. Third, the data already on the ground had to be reprocessed.

Many different approaches to these three issues were considered by the MODIS anomaly team. The approach chosen combined low risk for the spacecraft with minimal modification of ground software. At the time, the onboard star catalog was created and uplinked with J2000 coordinates and was rotated to MOD coordinates using the precession matrix computed on board. There are 7 constants used in the computation of this matrix. These constants could be set to zero without modifying the flight software. This would yield a precession matrix equal to the identity, and the resulting onboard attitude then would always be referenced to the J2000 frame – consistent with the J2000 ephemeris. This would fix the spacecraft pointing problem. In addition, with this approach no changes were needed in the DPREP system for processing future data. The DPREP system would receive J2000 quaternions from the spacecraft and would continue to use a J2000 ephemeris, so the DPREP coordinate frame mismatch would be removed with no additional effort or change in procedure.
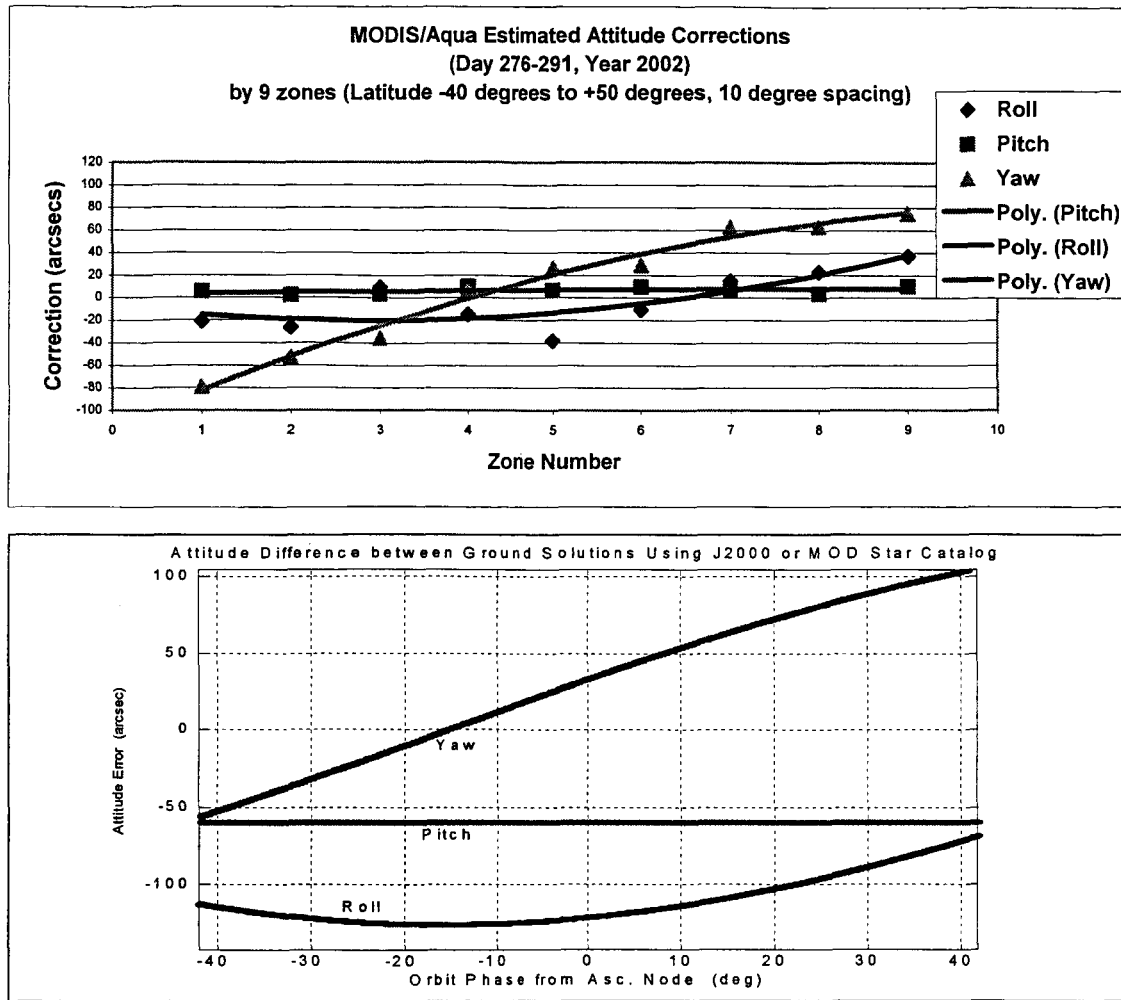
Figure 7. (*upper*) Attitude errors (arcsec) estimated by the MODIS instrument on Aqua (Ref. 6). (*lower*) Detail from Fig. 6 showing orbital phases corresponding to MODIS zone numbers.

To reprocess the existing data sets from the first ~8 months of the mission, we suggested pre-processing the telemetry files before passing them to DPREP. The OBC attitude quaternions in these early data sets are in the incorrect MOD frame. The attitudes can be read from the files, rotated into the J2000 frame, and rewritten. These corrected files then can be sent again to DPREP along with the J2000 ephemeris data. This makes the reprocessing exactly the same as normal processing for the future data sets, eliminating the need for creating a MOD ephemeris or for special bookkeeping to keep track of which ephemeris type was used with each data set. A utility was quickly specified, implemented, and tested by Flight Dynamics analysts and developers for performing the pre-processing of old telemetry data sets. It was verified that this method works as expected to produce correct attitudes for MODIS.

The spacecraft engineers and flight software personnel verified by simulations that zeroing the onboard star catalog precession constants would not endanger the spacecraft and that the perturbations should not even be large enough to make it leave Fine Point Mode. The zeroed precession constants were uploaded on March 5, 2003, and the attitude errors were successfully reduced as shown in Figure 8. The figure shows the roll and yaw angles, which prior to the upload had been exhibiting quarter-orbit roll-yaw coupling oscillations with peaks of ~150 arcsec in magnitude, approaching zero. The roll angle actually settled to a value slightly offset from zero (+11 arcsec) due to the 125 ms star tracker timetag error (see OBC Validation section). The figure shows the pitch angle, which prior to the upload was fairly constant at ~40 arcsec, approaching zero. The pitch angle also settled to a value slightly offset from zero (-13 arcsec) due to the 125 ms star tracker timetag error (see OBC Validation section). The pitch oscillations seen in Figure 8 settled to a peak-to-peak value of ~20 arcsec, and are due to the incongruity between the IRU and OBC cycles (see Ref. 8).
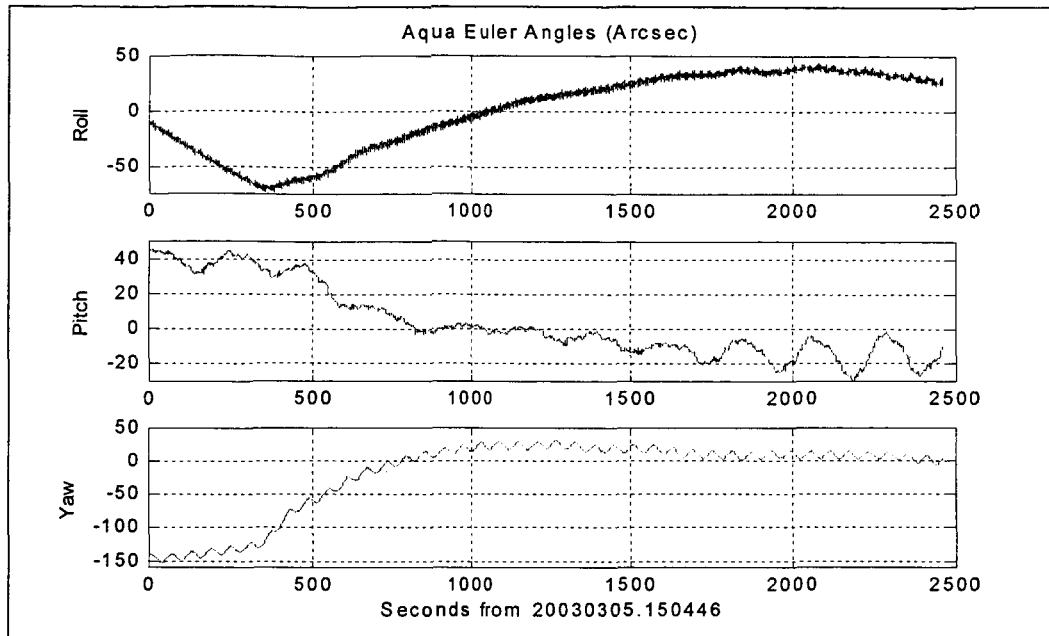
Fig. 8. Aqua Euler angles (arcsec) showing improvement when the onboard star catalog precession parameters were set to zero. The parameters were uploaded at approximately $t = 300$ sec on this scale.

CONCLUSIONS

The Flight Dynamics attitude team provided valuable support to the Aqua mission during launch support and throughout the early phases of the mission. The value of the work was illustrated in two fundamental capacities. First, the team met all of the requirements in the concept development, software and procedural development, and actual operational support for several critical activities, such as for the mode transitions which brought the spacecraft to its science data collection attitude. Secondly, the team applied their analytical techniques to improving the attitude accuracy of the spacecraft through such activities as sensor calibration, OBC validation, and anomaly resolutions. This resulted in not only the optimization of sensor parameters, but, in some cases, the uncovering of onboard errors through the systematic analysis of observed anomalies. Table 4 summarizes the attitude accuracy improvements made for Aqua as a result of the various activities and analyses undertaken by the Flight Dynamics attitude team.

Table 4. Summary of Flight Dynamics Activities to Resolve Anomalies and Improve Attitude Accuracy

Observed Anomaly	Size of Error / Attitude Accuracy Improvement	Resolution Result	FD Activity which Discovered or Resolved Anomaly
Large yaw excursions during EPM	Improvement of the 3σ ESA/TAM attitude error of ~30° (yaw)	Error in onboard magnetic field model; final TAM calibrations	Sensor calibration and analysis
Large pitch offset during thruster firings	~5° (pitch)	Plume impingement confirmed	Analysis
Large apparent relative misalignment between the star trackers	~0.2°	Error in onboard star tracker 1 nominal alignment	Sensor calibration
Large yaw excursions observed by MODIS	±150 arcsec (roll & yaw) -75 to +30 arcsec (pitch) (Ref. 7)	Coordinate system mismatch between onboard ephemeris and star catalog	OBC validation and analysis
Pitch/roll offsets between ground and onboard quaternions	~11 arcsec (roll) ~13 arcsec (pitch)	Error in onboard timetag for star tracker 1 (125 ms)	OBC validation and analysis
Small attitude oscillations on all 3 axes and associated variation in gyro biases	σ ≈ 8 arcsec (roll & yaw) σ ≈ 5.5 arcsec (pitch)	Ongoing: possibly due to a varying misalignment caused by thermal distortion	OBC validation and analysis
Periodic rate spikes leading to attitude errors	up to 2 arcsec (not discussed in this paper, but see Ref. 8)	Incongruity between IRU and OBC cycles	OBC validation and ground attitude determination

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